End-to-End Delay and Jitter Analysis in ATM Networks

Randall Landry and Ioannis Stavrakakis *

Department of Electrical Engineering and Computer Science
University of Vermont, Burlington, VT 05405
email: rlandry@emba.uvm.edu and stavraka@emba.uvm.edu

Abstract

In this paper the end-to-end performance evaluation of a tagged session is considered through the study of a tandem queueing network. A service discipline is adopted at each queue which allows for the study of First-Come First-Served (FCFS) as well as peak-rate-enforcing multiplexing schemes. A numerical approach is presented which allows for the computation of delay, jitter and inter-departure time distributions for the tagged cell stream. The cell inter-departure time probability distributions will be used to describe the tagged stream at the output of each queue, thereby facilitating the end-to-end delay and jitter analysis.

1. Introduction

Future Broadband-Integrated Services Digital Networks (B-ISDNs) based on technologies such as ATM will be required to provide Quality of Service (QOS) guarantees to a wide range of diversified users. A large portion of this user population will likely consist of real-time sources, and the performance measures expected to play a prominent role in evaluating their QOS include cell delay distributions and delay jitter (or cell delay variation).

Ultimately, the QOS delivered to a given session will need to be guaranteed (and computed) on a network-wide end-to-end basis. Deterministic bounds on delay have been derived in [1]-[4], where the traffic from each session is assumed to conform to pre-defined burstiness constraints. These approaches are based on worst-case performance and the bounds are extremely loose, resulting in the under-utilization of available resources when used for call admission purposes [5]. *Provable* statistical bounds have been derived in [6],[7] which also appear to be too loose to be of practical use in call admission. An alternative approach is to provide *approximate* statistical QOS guarantees [8]-[10] by modeling the traffic at the network edge (or within the network itself) and analyzing the resulting queueing behavior. While this approach has the advantage of simplicity, it generally yields only local guarantees at a single multiplexer, as opposed to the required end-to-end QOS guarantees. Secondly, the approximate approaches suffer from the traffic assumptions which must be made at the network premises (NP). Traffic patterns which are well-behaved at the network edge are typically subjected to significant distortion, or *jitter* as they are multiplexed within the network. Therefore, it is necessary to characterize the changes in a session's traffic profile in order to evaluate performance at subsequent multiplexing stages.

The computation of performance measures for an individual session, as well as the characterization of its output process, are challenging problems. In [11] a method is developed for

*Research supported by the Advanced Research Project Agency (ARPA) under Grant F49620-93-1-0564 monitored by the Air Force Office of Scientific Research (AFOSR)

calculating the cell inter-departure time distribution of a general renewal stream under a FCFS service policy. Statistics for the inter-departure process of an initially periodic cell stream in a FCFS multiplexer are also computed in [12] by assuming a first-order Markovian structure for the cell delay process.

Aside from the need to characterize the jitter induced in a cell stream at a multiplexer, it may also be necessary to reshape these distorted cell streams as they traverse the network, thereby re-enforcing a call's compliance with its contract specifications. The impact that this re-regulation has on the delay and jitter of a tagged session has been studied mainly through simulations.

The primary objective of this paper is to study the end-to-end performance of a tagged session as it is multiplexed and/or regulated at the NP. This is accomplished by introducing a non-work-conserving service discipline at each queue in a tandem queueing network which occasionally departs from the FCFS policy by enforcing a peak output rate (minimum cell inter-departure time) for one of the traffic classes (Class-1). Note that the formulated queueing model for a single multiplexer, which is described in section 2, can be applied to model devices such as the Spacer-Controller considered in [13]. When the peak-rate enforcer is disabled (by properly setting a key parameter), the policy becomes the standard FCFS policy considered in [11]-[12].

The queueing analysis presented in section 2.3 provides for the computation of probability distributions for cell delay and jitter of the tagged traffic, which is modeled as a memoryless cell inter-arrival process of arbitrary distribution. A method for computing the inter-departure time distribution for the tagged cell stream is also presented, which allows for the end-to-end delay and jitter analysis presented in section 3.

2. An ATM Multiplexer in Isolation

Consider a single tagged session which passes through a number of ATM multiplexing stages as it proceeds through the network in a connection-oriented fashion. Each site at which the tagged session is multiplexed with other traffic streams will be modeled here as a single-server queue with deterministic service time of 1 slot. The duration of a slot is equal to the transmission time of a fixed-size cell, and events of interest (cell arrivals and service completions) are assumed to occur at slot boundaries; the buffer capacity is assumed to be infinite. The adopted service policy at the queue will be the Peak Output-Rate-Enforcement (PORE) policy introduced in [14], which allows for the consideration of peak rate enforcement as well as simple FCFS service.

2.1. The PORE Service Policy

The proposed PORE policy is a service discipline associated with a specific class of interest (Class-1), which represents the tagged session. The rest of the traffic present in the system is treated in an indistinguishable manner under the PORE policy for Class-1 and, thus, is considered to form a single traffic class (Class-2 or background traffic).

As will become clear below, the PORE service strategy for Class-1 guarantees that cells belonging to this class are transmitted at a minimum spacing of X_{min} slots. The server operates according to the FCFS discipline except for those times when the FCFS server would place consecutive Class-1 cells on the output link at a distance of less than X_{min}. In this paper it is assumed that under the FCFS policy, Class-1 cells are served before the Class-2 cells which arrive over the same slot.

Let t_k denote the service epoch of the k^{th} Class-1 cell, defined as the beginning of the slot over which this cell is transmitted. Let $X_k = t_{k+1} - t_k$ denote the inter-departure time of Class-1 cells $k+1$ and k. Similarly, $\tilde{t}_k$ will mark the *potential* service epoch of the k^{th} Class-1 cell, which is defined to be the beginning of the slot at which all other cells that arrived prior to the k^{th} Class-1 cell have been served. Note that under the FCFS discipline, $\tilde{t}_k = t_k, \forall k \geq 1$.

The PORE service discipline can be described in terms of the following rules:

(a) Whenever $\tilde{t}_k - t_{k-1} < X_{min}$, the server delays the initiation of service to the k^{th} Class-1 cell by exactly $h_k = X_{min} - (\tilde{t}_k - t_{k-1})$ slots, which will be referred to as the *holding time* of the k^{th} cell for the remainder of the paper.

(b) During this holding time of length h_k, the server will provide FCFS service to Class-2 cells that may be present in the buffer. This implies that during the holding interval, up to h_k Class-2 cells can be served before the k^{th} Class-1 cell which arrived at an earlier time.

(c) When the holding time expires, the k^{th} Class-1 cell is served; thus, $t_k = \tilde{t}_k + h_k$, thereby ensuring that $X_{k-1} = X_{min}$.

Note that according to rule (b), the server abandons the FCFS discipline whenever a Class-1 cell is held ($h_k \geq 1$), and thus, it provides improved service to Class-2 compared to that under the FCFS policy. The PORE service policy reduces to the FCFS policy when $X_{min} = 1$, in which case $h_k = 0, \forall k \geq 1$.

Let the Class-1 cell inter-arrival process be denoted by $\{A_k\}_{k \geq 1}$, where A_k represents the inter-arrival time (in slots) between Class-1 cells k and $k+1$. It is assumed that $A_k \in [A_{min}, \infty) \subseteq \mathbf{Z}^+$, where $\mathbf{Z}^+$ denotes the set of positive integers. Class-2 traffic is considered to be the background traffic whose presence stands to corrupt $\{A_k\}_{k \geq 1}$ through the queueing process.

2.2. Discussion of the Multiplexer-Induced Jitter

In ATM networks supporting real-time applications, one of the most important measures of QOS is delay jitter, which describes the degree to which a session's cell stream has been distorted in the network. When a session experiences a large amount of jitter, or distortion to its traffic profile, extensive buffering may be required at the receiver in order for the original data stream to be recreated before being played back. Furthermore, an initially well-behaved cell stream can induce queueing problems and QOS degradation for existing sessions as it becomes distorted and potentially more bursty within the network.

One way to quantify the delay jitter induced in a given cell stream is through the probability distribution of cell delays and perhaps a measure of the difference between some lower and upper quantiles [13],[12]. A similar definition is simply the difference between the minimum and maximum delays experienced by cells belonging to a given session. In this paper a cell-level definition for jitter will be adopted to describe the amount of distortion introduced into the Class-1 cell stream.

Definition 1 *Let d_k denote the total queueing delay (in slots) of the k^{th} Class-1 cell, including the transmission slot. The jitter of the k^{th} cell is defined as*

$$J_k = d_{k+1} - d_k \quad \textit{for } k \geq 1. \quad \square \tag{1}$$

In terms of the quantities defined in the previous subsection, an equivalent definition of jitter is given by

$$J_k = X_k - A_k \quad \text{for } k \geq 1. \tag{2}$$

Note that J_k measures the degree to which the inter-arrival time A_k of Class-1 cells k and $k+1$ has been distorted, and it can take both positive and negative values. *Negative* jitter applies to those instances when Class-1 cells k and $k+1$ are transmitted at a spacing of less than A_k (cell clustering), while *positive* jitter applies to those times when cells k and $k+1$ are transmitted at a spacing of greater than A_k (cell spreading). Note that when the process $\{A_k\}_{k\geq 1}$ has a finite region of support (i.e. $A_k \in [A_{min}, A_{max}]$), the PORE policy completely eliminates a portion of the negative jitter by guaranteeing that $J_k \geq X_{min} - A_{max}$. It is also proven in [15] (Theorem 1) that the PORE policy does not increase cell spreading. In fact, numerical results indicate that this policy slightly reduces the positive jitter.

2.3. Queueing Analysis

In this section, an ATM multiplexer operating under the PORE service policy is studied in terms of performance measures associated with the Class-1 cell stream. The Class-1 inter-arrival process $\{A_k\}_{k\geq 1}$ is assumed to be i.i.d. with distribution $f_a(k)$, $A_{min} \leq k \leq A_{max}$. Note that a periodic process with period T can be considered when $A_{min} = A_{max} = T$ and $f_a(T) = 1$.

Class-2 traffic is modeled in terms of i.i.d. batches of cells of arbitrary distribution. The random variable b will denote the number of Class-2 cells (batch size) arrived over a slot, with a PMF denoted by $f_b(j)$, $0 \leq j \leq N^b$, where N^b denotes the maximum batch size for Class-2 arrivals.

The queueing system will be described in terms of the Markov chain $\{d_k, h_k\}_{k\geq 1}$, which is embedded at the sequence of time instants $\{t_k\}_{k\geq 1}$, where t_k marks the service epoch of the k^{th} Class-1 cell as defined earlier; d_k and h_k denote the total delay and holding time of the k^{th} cell, respectively. Let $S^L = \{(i,j) : L(A_{max}-1)+1 \leq i \leq (L+1)(A_{max}-1), 0 \leq j \leq X_{min}-1\}$ represent "level" L of the Markov chain $\{d_k, h_k\}_{k\geq 1}$. Conceptually, if the queueing system is at level L then there are at least L Class-1 cells in the queue, other than the Class-1 cell which is about to be served. Therefore, level '0' represents the only set of states from which the queue can potentially become empty at the beginning of the time slot over which the next Class-1 cell arrives.

Let the probability that the Markov chain $\{d_k, h_k\}_{k\geq 1}$ moves from state (i,j) at time t_k to state (i',j') at time t_{k+1} be denoted by $p(i,j,i',j')$. By mapping the quantities $p(i,j,i',j')$ into $p(\ell,\ell')$ through the relations $\ell = (i-1)X_{min} + j$ and $\ell' = (i'-1)X_{min} + j'$, the transition probability matrix $\mathbf{P}$ of the Markov chain $\{d_k, h_k\}_{k\geq 1}$ can be written as a stochastic matrix of the M/G/1 type:

$$\mathbf{P} = \begin{bmatrix} \mathbf{B_0} & \mathbf{B_1} & \mathbf{B_2} & \mathbf{B_3} & \cdots \\ \mathbf{A_0} & \mathbf{A_1} & \mathbf{A_2} & \mathbf{A_3} & \cdots \\ 0 & \mathbf{A_0} & \mathbf{A_1} & \mathbf{A_2} & \cdots \\ 0 & 0 & \mathbf{A_0} & \mathbf{A_1} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{3}$$

where the matrices $\mathbf{B_n}$ and $\mathbf{A_n}$, $n \geq 0$, have dimensions $(A_{max}-1)X_{min} \times (A_{max}-1)X_{min}$. Note that the matrices $\mathbf{B_n}$ consist of the transition probabilities for which $(i,j) \in S^0$ and

$(i', j') \in S^n$, while the matrices $\mathbf{A_n}$ consist of the transition probabilities for which $(i, j) \in S^1$ and $(i', j') \in S^n$.

The expressions for $p(i, j, i', j')$, where $(i, j) \in S^0 \bigcup S^1$, require lengthy derivations and are not included here; they can be found in [15]. Upon evaluating these transition probabilities, the system in (3) can be solved based on the matrix analytic techniques presented in [16]. The stationary probability vector $\boldsymbol{\pi}$ for $\mathbf{P}$ is mapped back into the space (i, j, i', j') to obtain the stationary probabilities for $\{d_k, h_k\}_{k \geq 1}$, given by $\pi(i, j)$, for $1 \leq i < \infty$, $0 \leq j \leq X_{min} - 1$.

Since the system state at time t_k is defined as (d_k, h_k), the PMF for cell delays of Class-1 is simply

$$Pr\{d = i\} = \sum_{j=0}^{X_{min}-1} \pi(i, j) \quad . \tag{4}$$

By considering the definition in (1), the jitter distribution is easily determined to be

$$Pr\{J = k\} = \sum_{i=1}^{\infty} \sum_{j=0}^{X_{min}-1} \sum_{j'=0}^{X_{min}-1} p(i, j, i+k, j')\pi(i, j) \tag{5}$$

Computing the PMF of the Class-1 cell inter-departure time X is not as straight-forward as computing that of J. From equations (1) and (2), the inter-departure time of cells $k+1$ and k is given as $X_k = d_{k+1} - d_k + A_k$. The Markov chain $\{d_k, h_k\}_{k \geq 1}$ does not provide adequate information to describe the inter-departure process. Hence, the system will be described by the Markov chain $\{d_k, h_k, A_k\}_{k \geq 1}$ in order to compute the PMF of X. Let $\tilde{p}(i, j, k, i', j', k')$ denote the transition probabilities and $\tilde{\pi}(i, j, k)$ denote the stationary probabilities for this Markov chain. It is easy to show that the PMF for the cell inter-departure process is given by

$$Pr\{X = n\} = \sum_{i=1}^{\infty} \sum_{j=0}^{X_{min}-1} \sum_{k=A_{min}}^{A'} \sum_{j'=0}^{X_{min}-1} \sum_{k'=A_{min}}^{A_{max}} \tilde{p}(i, j, k, n+i-k, j', k')\tilde{\pi}(i, j, k), \tag{6}$$

where $A' = min\{n + i - 1, A_{max}\}$.

Fortunately, the ominous numerical complexity involved with computing $\tilde{\pi}(i, j, k)$ can be avoided by realizing (as proven in [15]) that this quantity can be rewritten as $\tilde{\pi}(i, j, k) = \pi(i, j) f_a(k)$.

2.4. Jitter in a FCFS Multiplexer

Before studying the end-to-end performance of a tagged session, consider an ATM multiplexer which serves arriving cells according to the FCFS policy ($X_{min} = 1$). In order to provide for a simple interpretation of the multiplexer-induced jitter, the Class-1 arrival process is assumed to be periodic with period T slots; the Class-2 batch arrival process is assumed to be binomially distributed with mean rate λ^b and maximum batch size $N^b = 15$. In table 1 the squared coefficient of variation is given for the Class-1 cell inter-departure time process, denoted by C_X^2. Note that C_X^2 would be zero if no distortion were introduced into the periodic arrival stream. From table 1 it is clear that jitter is greatest for small periods T and high offered loads.

The multiplexer-induced jitter can also be quantified by observing the PMF for J as in Fig. 1. In this case the jitter PMF is plotted for $T = 20$ and the offered loads given in table 1. Notice that when the total load is 0.7, much of the periodicity is retained in the Class-1 arrival stream,

load	$T=5$	$T=10$	$T=20$
0.70	0.0236	0.0086	0.0028
0.80	0.0489	0.0209	0.0079
0.95	0.1160	0.0607	0.0296

Table 1. Squared coefficient of variation for cell inter-departure time (C_X^2).

which is illustrated by the fact that most of the probability mass exists at $J = 0$. However, as the load increases to 0.95, much of this mass is redistributed and the Class-1 arrival process no longer resembles a periodic source. It is also interesting to note that the jitter PMF appears to be symmetric around zero when the service policy at the multiplexer is FCFS. This symmetry disappears when a peak output rate is enforced ($X_{min} > 1$), as shown in [14].

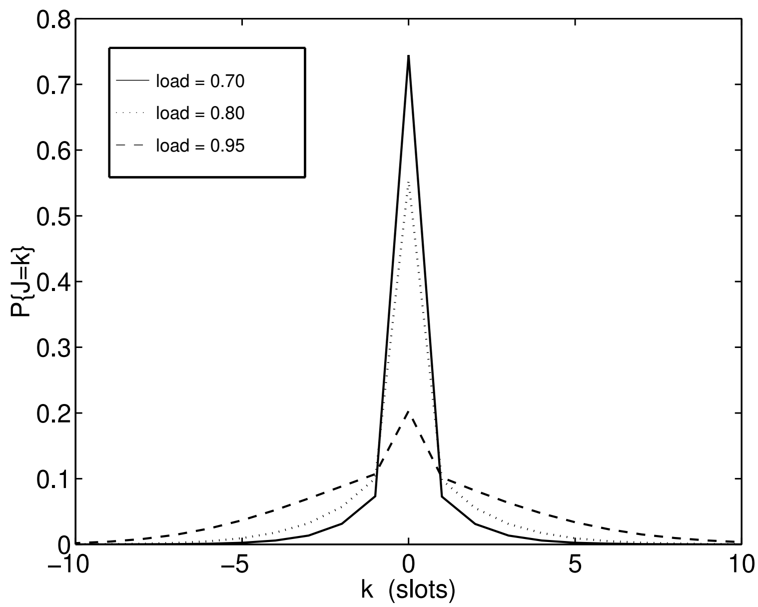

Figure 1. Jitter PMF for $T = 20$ and various loads.

3. End-to-End Performance Evaluation

The tandem queueing system used for the network-wide performance evaluation of the tagged session is shown in Fig. 2. Note that a similar network of FCFS servers is considered in [17]. The PORE service policy will be adopted at each node so as to allow for the consideration of peak-rate enforcement within the network. The tagged session is assumed to be routed through N nodes and its cell inter-arrival process at node 1 will be periodic, which represents a CBR source at the network edge. In order to simplify notation, the Class-1 cell inter-arrival (inter-departure) process at node i will be denoted simply as A^i (X^i). The arrival process at node i

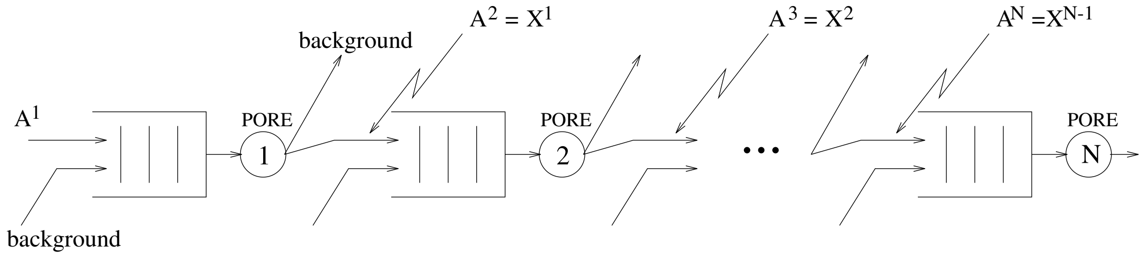

Figure 2. Tandem queueing network for end-to-end performance evaluation.

($2 \leq i \leq N$) consists of the tagged session (Class-1) inter-departure process from node $i-1$, and some background traffic (Class-2).

It will be assumed that the background traffic arriving at each node along the path in Fig. 2 is independent from that of all other nodes in this path. Implicit in this assumption is the presence of a large-scale networking structure, in which there exists a large number of independent sessions and a large number of total nodes (only N of which serve the tagged session). In such a network, it is expected to be reasonable to assume that, at the output of each node, most of the un-tagged sessions (background traffic) are split, or routed along paths which are different from that of the tagged session.

The analysis presented in the previous section for a single queue can be applied successively to each node along the path and the PMF for the inter-departure process at node N can be used to establish the amount of jitter induced in the cell stream of the tagged session over all N hops. In regards to the end-to-end delay analysis, recall that the cell delay PMF is computed at each node along the path. Therefore, under the assumption that delays are independent from one node to the next, a simple convolution of the individual PMF's yields the end-to-end delay distribution. While this is probably a reasonable assumption under a FCFS ($X_{min} = 1$) policy at each node, the cell spacing action when $X_{min} > 1$ is expected to introduce correlation into the inter-node cell delay process. However, the mean end-to-end cell delay is easily computed as the sum of the mean delays at each node without making any assumptions regarding dependencies in the inter-node delay process. Furthermore, it is a simple matter to consider propagation delays by adding these to the resulting queueing delays at each node.

To illustrate the end-to-end performance evaluation of a tagged session, the following example will be considered. The tagged session will originate as a periodic source at node 1 with period $T = 5$ and will pass through $N = 5$ multiplexing stages. The background traffic at each node is assumed to consist of 10 identical Bernoulli streams each with rate 0.07, resulting in a total offered load of 0.9 at each multiplexer. The relatively high load at each node, together with the small period of $T = 5$, is adopted to provide a scenario in which significant jitter is induced into the tagged cell stream (see table 1).

The squared coefficient of variation for the Class-1 arrival process (denoted by C_i^2 for node i) is plotted in Fig. 3 as a function of the node index when each PORE server is enforcing identical minimum inter-departure times of either 1, 3 or 4 slots. Note that because the arrival process to node 1 is periodic, $C_1^2 = 0.0$ for each case. As expected, C_i^2 increases with i for all values of X_{min}. However, depending upon the peak rate being enforced by each of the servers, the rate of increase, as well as the magnitude, of C_i^2 varies greatly. Under a FCFS policy at each server,

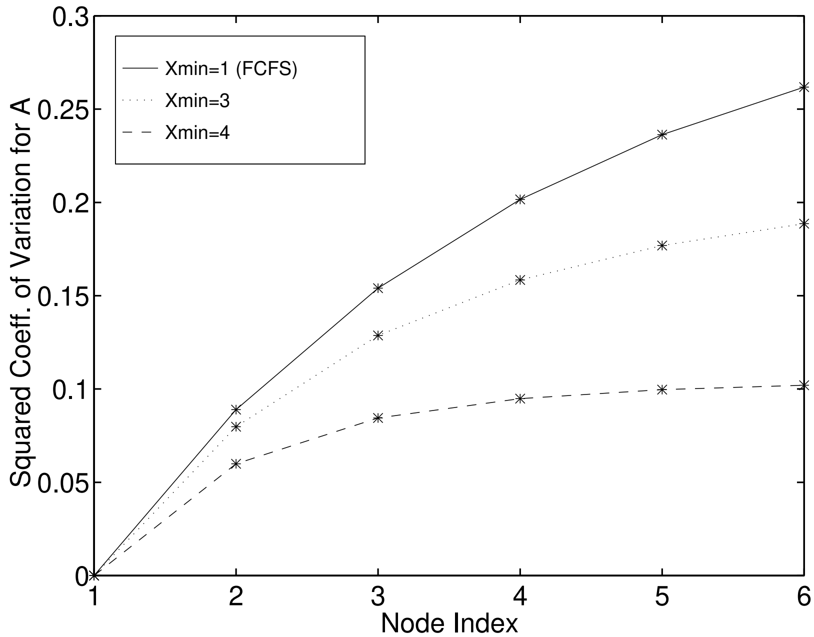

Figure 3. Squared cofficient of variation for the cell inter-arrival process to each node.

the tagged cell stream is changing significantly as it enters node 6, and the induced jitter is quite large. A noticeable improvement in the variability of the tagged cell stream is observed when X_{min} increases. In fact, when $X_{min} = 4$ at each of the PORE servers, C_i^2 is always smaller than 0.1 and, thus, the traffic profile would remain relatively constant. This has also been verified in terms of the marginal PMFs for cell inter-arrival times, which are not included here due to space limitations.

The price to be paid for such jitter reduction in the tagged session is, of course, increased cell delays as shown in Fig. 4, where the cumulative mean delay is plotted as a function of the node index. The total mean delay appears to increase linearly as a function of the node index and the rate of increase is clearly dependent upon the value of X_{min}.

Figures 3 and 4 point to a fundamental tradeoff in providing QOS guarantees in ATM networks. For real-time applications with strict delay deadlines there is certainly an upper limit on the amount of traffic shaping which can be performed throughout the network. In such a case, the tradeoff between violating deadline constraints and violating either jitter constraints or a declared peak rate, needs to be considered carefully. It should be noted, however, that the mean cell delay does not provide adequate information about the delivered QOS in terms of end-to-end delay. Although the mean end-to-end delay can be significantly greater when a peak rate is strictly enforced, as seen in Fig. 4, the variability in end-to-end delays is expected to be much smaller. Therefore, as the jitter decreases with peak rate enforcement, and the mean cell delays increase, the delay distribution should possess a more narrow region of support, which is desireable when providing QOS guarantees based on statistical delay bounds [5].

The computation of higher moments for the end-to-end cell delay is currently under investi-

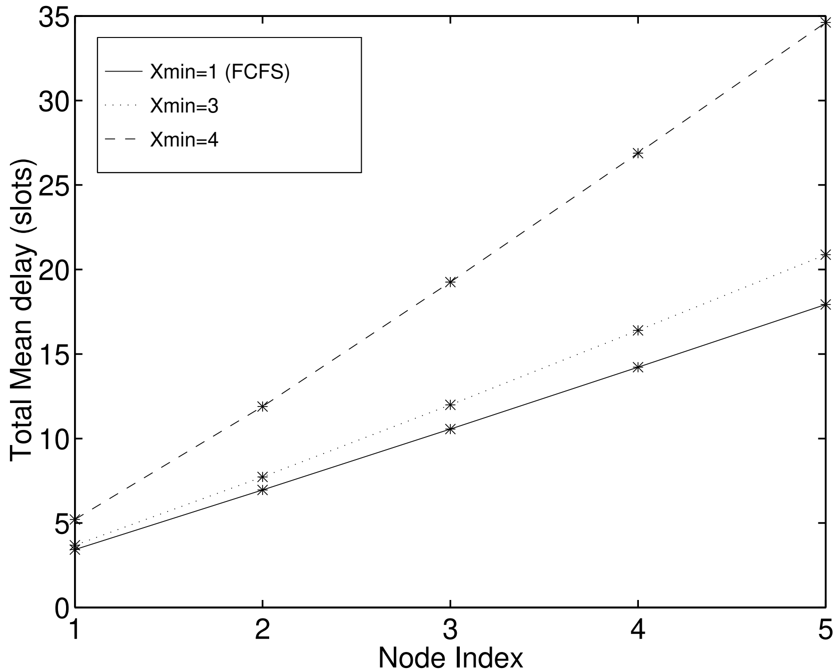

Figure 4. Total mean queueing delay as a function of node index.

gation. Simulation studies are also being conducted in order to more carefully study the above tradeoffs, as well as the validity of the assumptions made in the present work.

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